Semi-Annual Status Report
for the Period
July 1, 1966 - December 31, 1966

An Experimental Investigation of Radiation Effects in Semiconductors

National Aeronautics and Space Administration
Washington, D. C.

Research Grant No. NsG 22862

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Introduction

Irradiation of semiconductors with high energy radiation, neutrons, gamma rays, and fast electrons, introduce vacancies and interstitials that diffuse through the lattice and associate with impurities or other defects to form complex defect centers. The nature of the defect centers depends upon the concentration of oxygen, the concentration and type of dopant, and the temperature of the irradiation. The work carried out under this grant is intended to provide information about the microscopic nature of the defects, the nature of the defect interaction with the lattice, and the position of the energy levels associated with the various defects. Two techniques have been used in these investigations. The first considers the nature of the luminescence resulting from recombination of a free minority carrier with a majority carrier bound at the defect. The second considers the effects of irradiation upon the conduction of highly doped material. The latter technique has contributed significantly to a better understanding of these conduction processes.

Recombination Luminescence

Extensive measurements of the recombination luminescence of samples maintained near liquid helium temperature have been completed on a variety of n- and p-type silicon samples having a considerable variation in oxygen content. Samples were irradiated with gamma rays and with fast neutrons. The spectrum observed after 10^8 Roentgen of Co^{60} is the same for both n- and p-type material, but the intensity is greater in the p-type material.

The spectrum of luminescence of irradiated Czochralski silicon, both n- and p-type, consists of two sub-spectra with the most intense peaks located at 0.7905 and 0.9707 eV. The structure found on the low energy side of the 0.9707 eV peak is nearly replicated on the peak at 0.7905 eV. This structure appears to result from recombination with the assistance of phonons, the energies corresponding to phonons at the boundaries of the Brillouin zone.

The pattern at low energy, with a zero phonon line occurring at 0.7905 eV, is found only in Czochralski silicon indicating that the defect responsible for this luminescence is depressed in samples having a low oxygen content.

The zero phonon lines have been measured with as high a resolution as is possible. The width decreases with decreasing temperature. The narrow line at 0.7905 eV was found to be 0.0006 eV when measured with an instrumental resolution of 0.0003 eV. For a sample temperature of 7°K, as measured for this experimental set-up, kT is essentially the same as the line width, indicating that this width results from the thermal population of the carriers in the band. This result strongly supports the suggestion that the luminescence arises from the recombination of a free hole with a bound electron.

A portion of the results of this experiment were reported at the International Conference on the Physics of Semiconductors, Tokyo, Japan, in September, 1966. A preprint of that paper is attached to this report. A copy of an abstract to be presented at the American Physical Society at Chicago in March, 1967, on this topic is also attached. Mr.

Robert Spry has completed the taking of all the data that he will need for his Ph.D. thesis. This is now being written up and will be submitted in the next few weeks.

Tunneling Between a Semiconductor and a Superconductor

Work has continued in the past six months on the problem of measuring the impurity band density of states in near degenerate semiconductors by tunneling from a metal. Emphasis in this effort has been shifted from germanium to silicon as a result of the work of Conley, Duke, Mahan and Tiemann[1] on degenerate antimony doped germanium, in which tunneling was observed through the Schottky barrier under an indium metal contact. Their results indicate that the surface barrier in germanium is sufficiently thick at the doping level of impurity band formation, near 10^{17} cm^{-3}, that the tunnel current is too small to measure. The barrier layer is thinner in p-type silicon at the doping corresponding to the onset of impurity band conduction because the corresponding boron concentration is about 10^{19} cm^{-3}, or a factor 100 greater than in germanium.

The use of an indium metal point in the point contact tunneling apparatus has been investigated. A clean one micron point is cut on indium wire by use of a modified microtome. The contact diameter can be controlled in the range of 5 to 20 microns by adjusting the applied force to the point in the range 1 to 100 milligrams. It is believed that the softness of the indium even at cryogenic temperatures allows one to make a contact with pressures less than 1 Kg/mm^2. The electronic equipment associated with the tunneling experiment has been improved by the design of a noise-free transistorized voltage sweep with low output impedance. Helmholtz coils have been incorporated into the Dewar containing the point contact tunneling apparatus. The point contact apparatus has been modified to permit observation of the sample and point contact in the liquid helium through a binocular microscope as the experiments are carried out.

Although reproducible results have been obtained with the point electrode technique, considerable success has also been found with samples made from an alloyed indium contact or silicon. A systematic study of samples of various resistivities is now underway using an indium contact.

Considerable effort was expended during the past six months on producing tunneling samples of silicon with lead as the superconductor. The silicon was cleaned, oxidized a known amount, and then coated with an evaporated layer of lead. Although considerable difficulty was experienced in obtaining reproducible results with this technique, several samples demonstrated interesting anomalies at zero voltage in the I vs V plots.[2] These particular preparation techniques have been abandoned in favor of the use of indium as a contact.

<u>Minority Carrier Lifetimes in Irradiated Materials</u>

Attached are preprints of a paper presented at the International Conference on the Physics of Semiconductors, Tokyo, Japan in September, 1966 on this topic. The remainder of the material on this subject that formed the Ph.D. thesis of Dr. Ralph Hewes is being prepared for publication.

Thermal Stability of Irradiation Induced Defects

Attached are reprints of a paper entitled "Annealing of Neutron-Irradiation-Induced Changes in Impurity Conduction in Antimony-Doped Germanium" that appeared in the Proceedings of the International Conference on the Physics of Semiconductors.

Personnel

Dr. E. L. Wolf, Mr. Ralph Hewes, Mr. Robert Spry, Mr. Colin Jones and Mr. Eric Johnson were employed for all or part of the time during the past six months.

References

1. J. W. Conley, C. B. Duke, G. D. Mahan, and J. J. Tiemann, Phys. Rev. 150, 466 (1966)
2. L. L. Chang, L. Esaki, and F. Jona, Appl. Phys. Letters 9, No. 1, 21 (1966)

Recombination Luminescence in Irradiated N-type Czochralski Silicon*

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Recombination luminescence of optically excited electron-hole pairs has been seen in Co^{60} gamma ray- and neutron-irradiated n-type Czochralski silicon. The observations at liquid nitrogen temperature previously reported[1] have been extended to liquid helium temperature where the greater luminescent intensity makes it possible to carry out the measurements at higher resolution. Two similar complex luminescence patterns are seen in both neutron and gamma irradiated material, with many of the details of the high energy complex replicated at lower energy with a uniform energy separation of 0.180 eV. Especially intense bands having thermally broadened linewidths appear at 0.971 eV and 0.791 eV. These are thought to be caused by phononless recombination between free holes and electrons in the ground states of two different defects, 0.194 eV and 0.374 eV below the conduction band minimum. The less intense bands of both patterns are thought to be caused by the same mechanism but with the emission of various phonons.

*Work supported in part by National Aeronautics and Space Administration Grant NsG 228-62.

[1] R. J. Spry, Bull. Am. Phys. Soc. 11, 193 (1966).

Abstract for the March 27-30 meeting of the American Physical Society in Chicago, Illinois.

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